Perform CGI spectroscopy using AMICI prism with Direct Imaging Camera

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Change Description

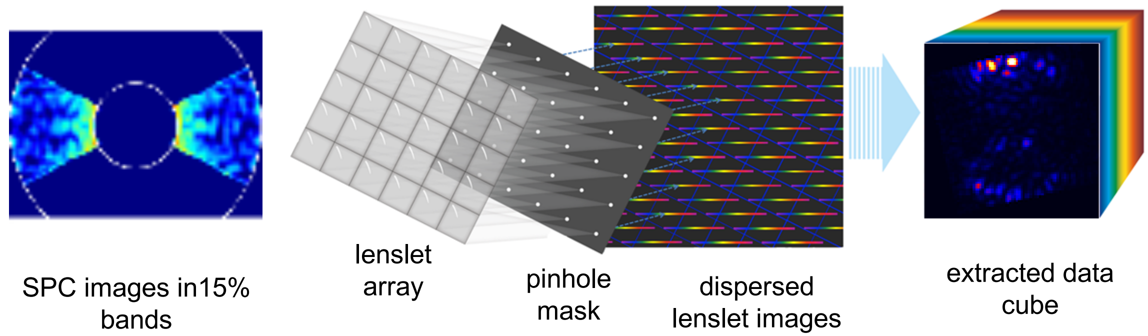
- Change Requested:
  1. Remove IFS optics, IFS Camera and associated electronics, thermal H/W, operations (such as IFS centroiding by PACE), etc.
  2. Add two direct-vision dispersion prisms (aka Amici prisms) on CSAM, and perform spectroscopy with DI
     - Additional engineering filters for dark hole digging, as demonstrated with SPC 18%
     - Change spectrum extraction algorithms (IPAC?, SITs?) Part of Ground Systems PDR?

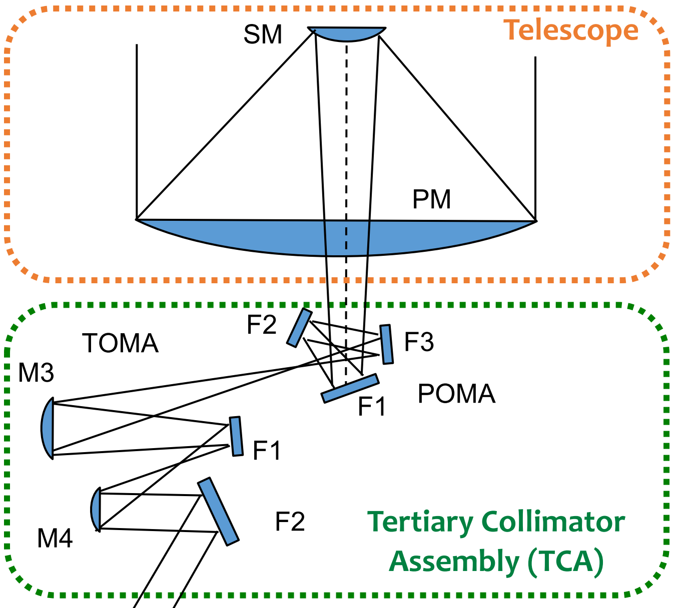
- Rationale:
  1. Simplify CGI, reduce mass and power
  2. Help CGI fit in cost cap

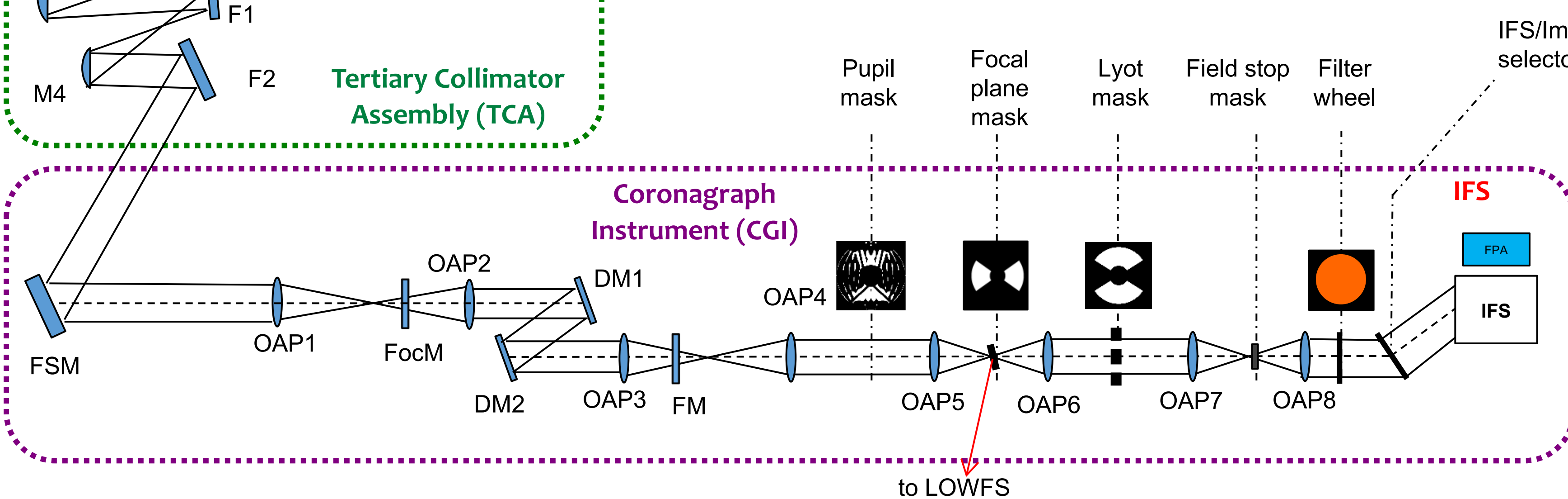
WAS

Shaped Pupil Spectroscopy Mode

The IFS uses two 15% bands (Band #2 and Band #3) to produce R≥50 spectra from 600 to 900nm at IFSCAM



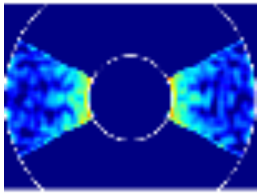




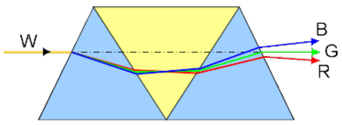
IS

Shaped Pupil Spectroscopy Mode

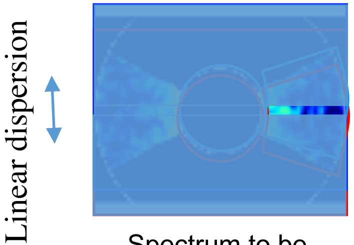
The Amici prisms disperse the 15% bands (Band #2 and Band #3) to produce R≥50 spectra from 600 to 900nm at DICAM



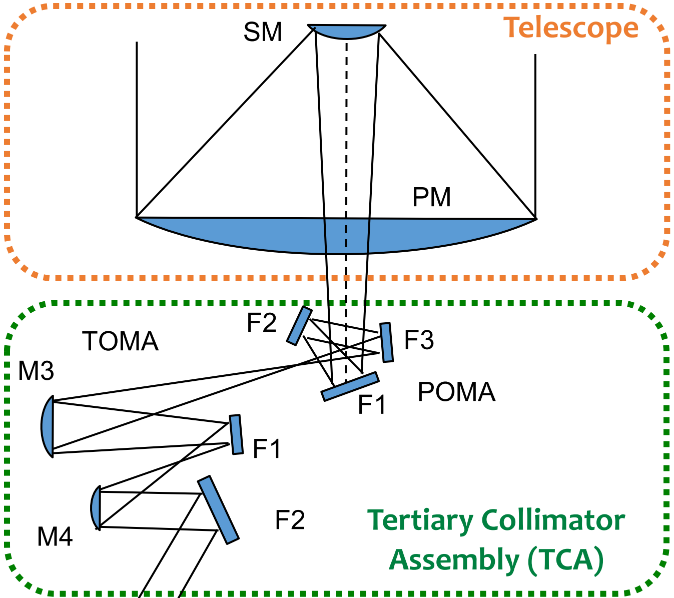
SPC images in 2 15% bands

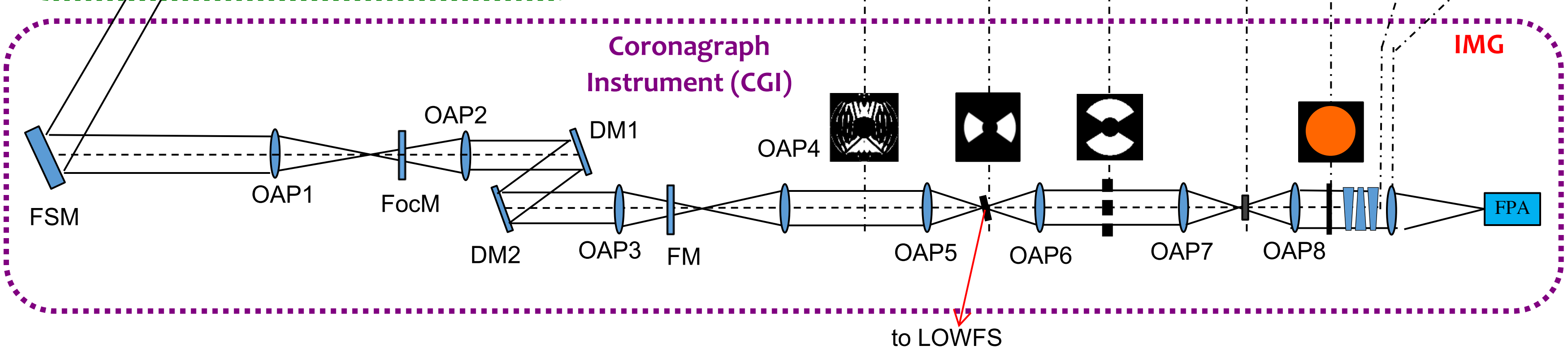


Amici prism

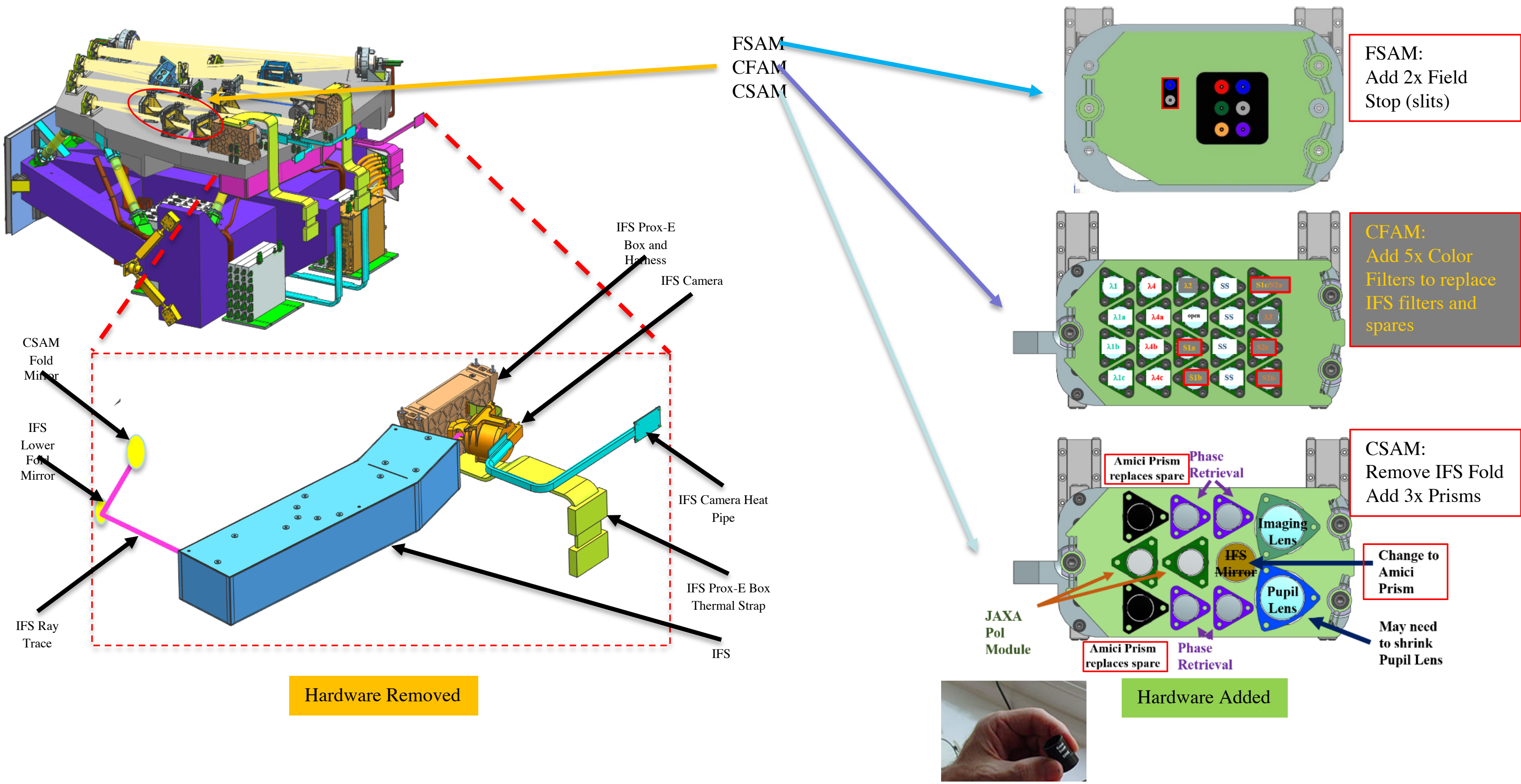


Spectrum to be extracted from dispersed images. Assume we also have the direct image and speckle field.





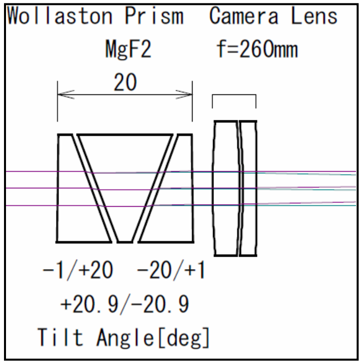
IFS Components on CGI



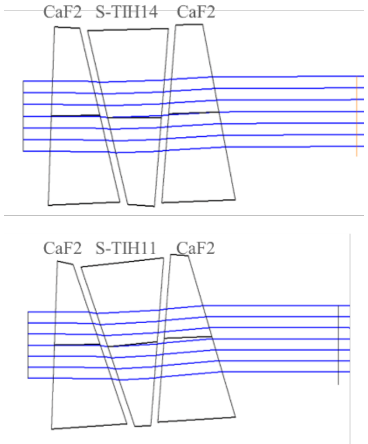
Courtesy of Brandon Creager and Derek Barnes

Added Prism Assemblies (2X) similar to Existing Polarization Modules

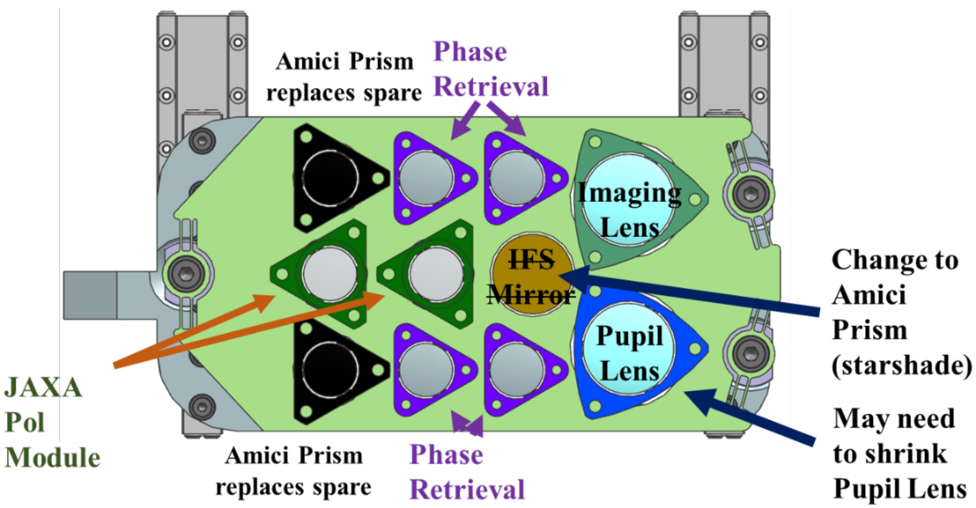
- Prism design almost identical to Polarization Module
  - Triplet plano prisms and doublet imaging lens
- CGI and JAXA team have been working together on opto-mech design
  - Room temperature
- Polarization module PDR tentatively planned July 29-30, 2019
- Can join forces with GSFC IFS team
- High confidence in engineering design to reach PDR level by CGI PDR time



JAXA Polarization Module (2X)
Courtesy of Motohide Tamura

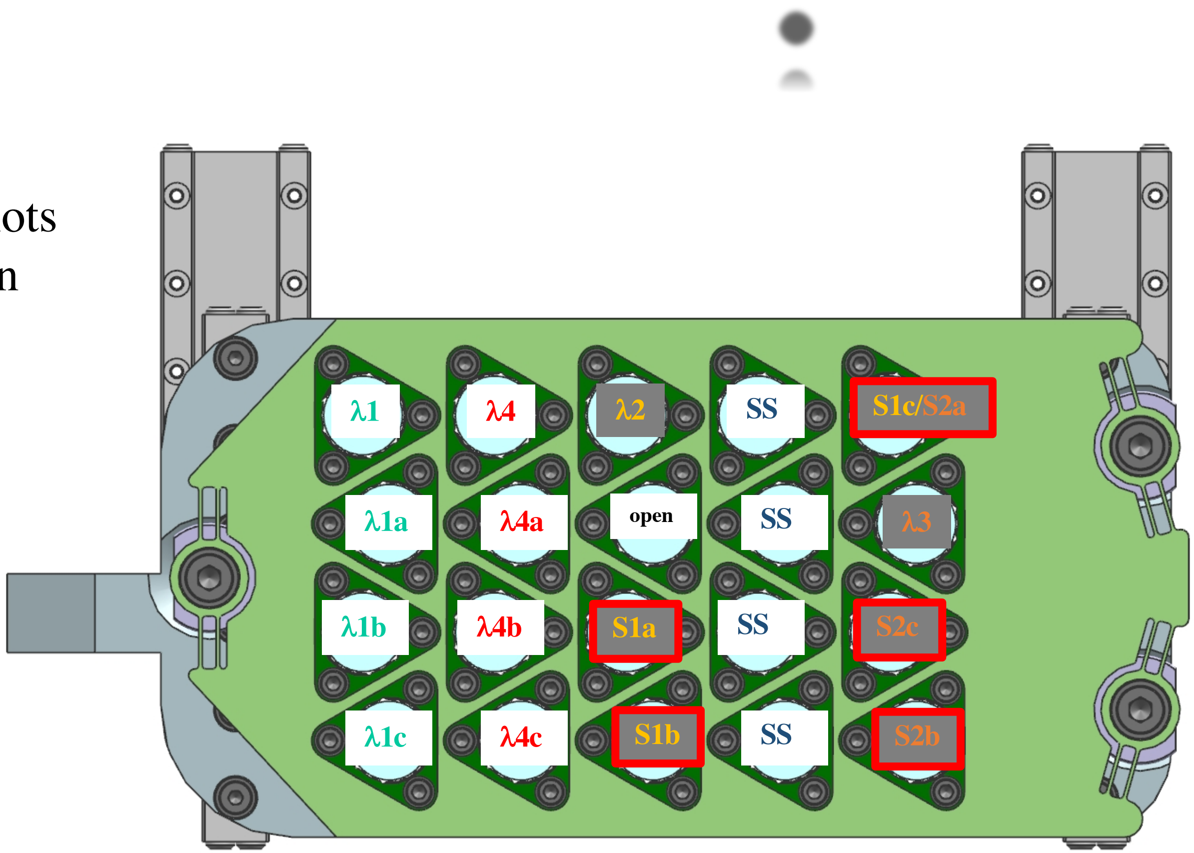


Proposed CGI planet spectrum prisms (2X, band #2 and band #3)
Courtesy of Tyler Groff and Qian Gong (GSFC)



Added Five Color Filters to existing Spare Slots

20 Filter Slots currently on CFAM

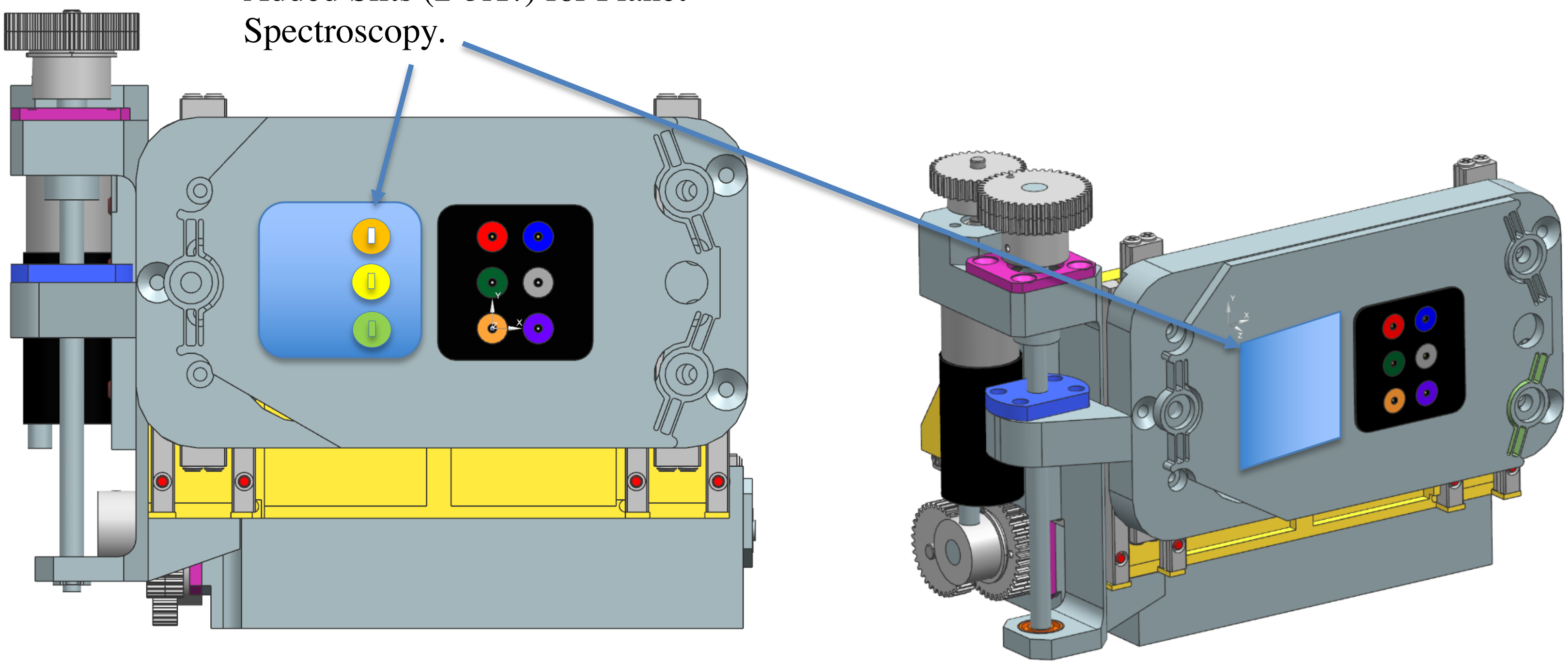


Replace IFS filters and spare slots (total 5X)

Courtesy of Derek Barnes

Added slits (2X) to Field Stop Alignment Mechanism

Added Slits (2-3X?) for Planet Spectroscopy.



New hard-wares can be accommodated with existing space on the JPL “plates”, do not require modification of the MPIA PAMs

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Mass and Power Impact

This change brings us to meeting PDR mass margin

MASS Savings Estimate v3 5-13-19

IFSCam Related Components	Mass Saved (kg) *	Applicable MEL Row	CogE
IFS Cam:	**7.4**		P. Morrissey
IFS Camera Head (detector, etc)	5.3	51	P. Morrissey
IFS Camera Prox-E (includes preamp)	2.1	59 -60	P. Morrissey
IFS Optics:	**6.5**		T. Groff
IFS Assembly	6.2	43	T. Groff
IFS Fold Mirror/Mount	0.3	36 - 37	K. Patterson
Structure:	**7.0**	N/A. Wag	J. Lam
Thermal HW:	**7.0**	N/A. Wag	J. Kempenaar
Total Savings Estimate:	**27.8**		
Ave CBE (current):	298.3		
Margin (current) vs current Allocation:	15%	WAS	
Ave CBE (after savings estimate):	270.5		
Margin (after savings est) vs current Allocation:	23%	IS	

Current CGI Mass Allocation from S/C (kg): 350
Mass margin (%) = (mass allocation – mass CBE) / mass allocation
* Based on MEL Ph B draft v11

This change brings us closer to meeting the PDR power margin

POWER Savings Estimate v3, 5-13-19

IFSCam Related Components	CGI Instrument Mode (W) OPS §	Standby	Survival	Applicable PEL Row †
Camera (detector & preamp)	*	N/A	N/A	11 - 12
Camera OPS Heater	See	N/A	N/A	61
Prox Elex	note	N/A	N/A	17
Prox Elex OPS Heater	below	N/A	N/A	65
Cam I/F Elex (CIE) - within ISE ¥	??	N/A	N/A	101
Camera Decon Heater	N/A	4.0	N/A	69
Prox Elex Survival Heater	N/A	16.9	16.3	89
Total Savings Estimate:	**0.0**	**20.9**	**16.3**	
Ave CBE (current):	299.1	244.4	217.3	
Margin (current) vs current Allocation:	25%	8%	3%	WAS
Ave CBE (after savings estimate):	299.1	223.5	201.0	
Margin (after savings est) vs current Allocation:	25%	16%	11%	IS

Current CGI Power Allocations from S/C: 400 265 225
Mass margin (%) = (mass allocation – mass CBE) / mass allocation
* PEL power estimates already factor in running only one of either IFSCam or DICam at a time
§ Based on 'Calibration' power state in the PEL, which is currently the highest power draw state
† Based on PEL Ph B draft v32b
¥ Power dissipated at the CIE will be reduced by this amount given removal of IFSCam

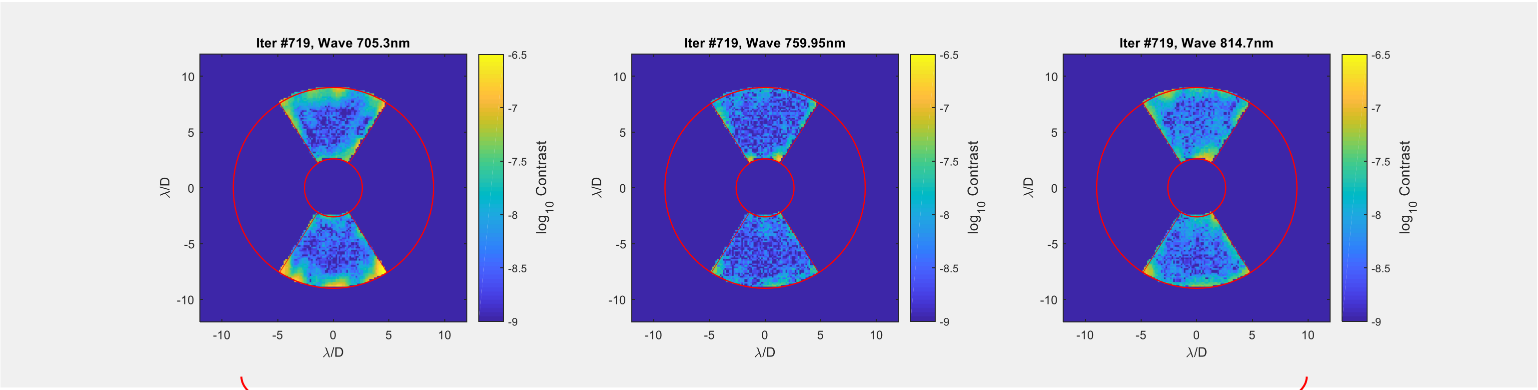
Courtesy of Jeff Bixler

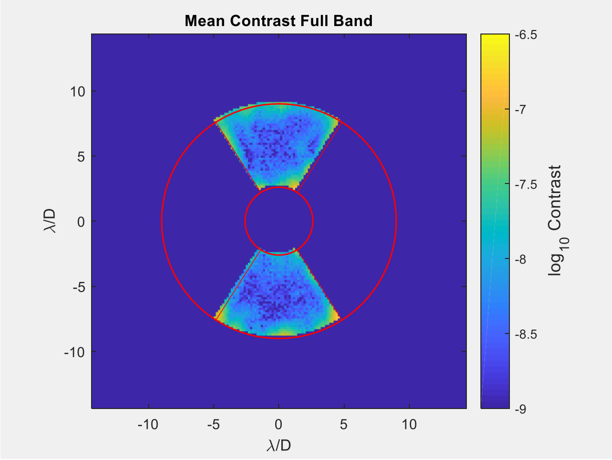
Amici Prism – First Round Concept of Operations

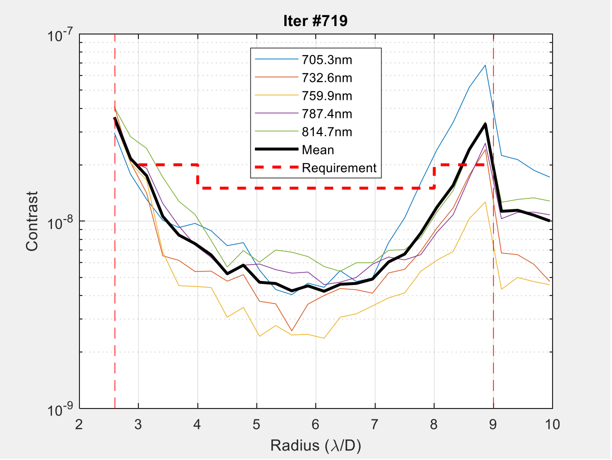
1. Dig the dark hole with a bright reference star
   - 3 sub-band engineering filters sequentially, no prism in the path.
     - This is exactly the way we do other imaging modes.
       - We have three reference images, one at each sub-band (some info on chromaticity of speckles)
2. Conduct observations with target star, first using full band filter
   - Obtain a direct image of the planet(s), using RDI, in 10's of hrs
     - Get some full band planet PSF information, location of the planet, brightness of the planet, some systematic behavior of the speckle fields (full band, maybe even some sub-band).
3. Go back to reference star and create deep dark hole at the planet location
   - This could compensate for no ADI, and the unlikeliness of success of PCA-like techniques with the slit
   - Also can make the coronagraph more drift-resistant (suppressing the field cross term $E^*\Delta E$)
4. Conduct spectroscopy
   - We now place the prism in the beam path.
   - We still have the option to use RDI to further chop out speckle drift
     - we can trade among three different ways: slit, tiny field stop, or slit-less modes.

Dark hold "digging" with DICAM demonstrated at HCIT

- Three sub-bands sequentially with DICAM
- Full band (18%) lab results meet requirement







Courtesy of David Marx

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BTR6 Requirement met with margin

assuming ~ 13 pixels per spectral element in Amici

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WFIRST Exoplanet Yield Among Known Planets: EB Amici Spec — viewed: 5/8/2019

EB Amici Spec — RDI : Δmag = 3.0 — 20% time on Ref — Setup time 12 hrs/pl — 1 Planets

Mode	CG	λ, nm	Δλ, nm	SNR	k_pp	Mission Life	time, hrs	set:	600	hrs max /pl.
EB Amici Spec	Amici Phase B	730	109.5	10	2.0	100%	70		0	hrs all planets

EM PC SRR

No.	Pl. Name	Vmag	Sep (mas)	WA (λ/D)	Critical SNR	Fl Ratio, ppb	Time Margin	t tar + tref, hrs	SMA (AU)	det tn e/p/h	dQE	pl thput
1	EB Fiducial Planet	5.0	300	4.72	87.7	50.0	93%	8	3.31	3.04	0.37	1.39%
12	eps Eri b	3.8	487	7.66	12.3	4.8	-100%	217.4	3.39	3.04	0.37	1.38%
52	GJ 832 b	8.7	487	7.66	9.5	3.7	-100%	-1738160.3	3.46	3.04	0.27	1.38%
21	HD 219134 h	5.6	417	6.57	6.3	2.8	-100%	-1455.6	3.02	3.04	0.31	1.40%
46	HD 87883 b	7.6	178	2.81	5.2	4.2	-100%	-141982.1	3.60	3.04	0.26	0.51%
57	HD 95872 b	9.9	487	7.66	5.2	2.0	-100%	-6220994.0	5.20	3.04	0.26	1.38%
40	HD 154345 b	6.8	190	3.00	4.7	3.7	-100%	-29328.1	3.84	3.04	0.26	0.64%
26	HD 190360 b	5.7	223	3.51	4.5	3.5	-100%	-1560.5	3.94	3.04	0.30	1.13%
25	HD 190360 c	5.7	224	3.53	4.4	3.5	-100%	-1553.1	3.96	3.04	0.30	1.13%
32	55 Cnc d	6.0	394	6.20	4.1	1.8	-100%	-4655.4	5.47	3.04	0.28	1.40%
16	47 UMa c	5.1	236	3.72	4.0	3.2	-100%	-408.7	3.60	3.04	0.35	1.23%
13	bet Pic b	3.9	438	6.89	3.7	1.6	-100%	-209.4	9.54	3.04	0.36	1.40%
23	psi 1 Dra B b	5.7	181	2.85	3.5	2.8	-100%	-6738.8	4.43	3.04	0.27	0.51%
58	GJ 328 b	10.0	199	3.13	3.4	2.7	-100%	-1288033.0	4.50	3.04	0.26	0.84%
36	HD 217107 c	6.2	265	4.16	2.7	1.6	-100%	-3591.5	5.86	3.04	0.27	1.40%
19	HD 160691 c	5.2	322	5.07	2.7	1.8	-100%	-448.0	5.54	3.04	0.31	1.39%
39	HD 100546 b	6.7	495	7.79	2.3	0.9	-100%	-60806.6	53.00	3.04	0.26	1.40%
45	HD 114783 c	7.6	218	3.44	2.3	1.8	-100%	-29861.23	4.92	3.04	0.26	0.99%
56	GJ 676 A c	9.6	354	5.57	1.9	1.3	-100%	-319385.5	6.60	3.04	0.26	1.39%
37	HD 134987 c	6.5	237	3.73	1.9	1.5	-100%	-4021.0	5.80	3.04	0.28	1.23%
35	HD 219077 b	6.1	193	3.04	1.8	1.4	-100%	-7442.7	6.22	3.04	0.27	0.64%
41	HD 150706 b	7.0	215	3.38	1.5	1.2	-100%	-18130.9	6.70	3.04	0.26	0.99%
15	HD 114613 b	4.9	239	3.75	1.5	1.2	-100%	-221.3	5.34	3.04	0.37	1.23%
24	HD 142 c	5.7	235	3.70	1.5	1.2	-100%	-1141.3	6.80	3.04	0.30	1.23%
10	tau Cet f	3.5	336	5.29	1.1	0.7	-100%	-30.6	1.33	3.04	0.37	1.39%
18	47 UMa d	5.1	487	7.66	1.1	0.4	-100%	-1122.6	11.60	3.04	0.30	1.38%
44	HD 92788 c	7.3	274	4.32	0.9	0.5	-100%	-27497.8	10.50	3.04	0.26	1.38%
42	HD 92987 b	7.0	200	3.15	0.7	0.6	-100%	-22548.8	9.62	3.04	0.26	0.84%
20	51 Eri b	5.2	407	6.41	0.7	0.3	-100%	-1450.8	13.20	3.04	0.29	1.40%
47	HD 13724 b	7.9	258	4.06	0.6	0.4	-100%	-78225.7	12.40	3.04	0.26	1.41%
34	HR 2562 b	6.1	547	8.61	0.4	0.2	-100%	-21992.5	20.30	3.04	0.26	0.87%
30	HR 8799 e	6.0	391	6.15	0.3	0.2	-100%	-5286.3	16.99	3.04	0.27	1.40%
29	HR 8799 d	6.0	552	8.69	0.3	0.1	-100%	-16553.8	24.00	3.04	0.26	0.87%
31	HR 8799 c	6.0	487	7.66	0.1	0.1	-100%	-7043.8	38.00	3.04	0.27	1.38%

Note that the requirement (BTR6) with the 50 ppb flux ratio fiducial planet, *is* met in all cases

EB Amici Spec — **CBE**

EB Amici Spec *7.0 hrs* *EB Fiducial Planet*

Variance rates for det. noise sources		
planet shot	2.2E-02	*e/SR/s*
speckle shot	4.8E-03	*e/SR/s*
zodi shot	9.1E-04	*e/SR/s*
dark noise	7.3E-03	*e/SR/s*
CIC noise	3.8E-03	*e/SR/s*
Lumines noise	7.0E-05	*e/SR/s*
read noise	0.0E+00	*e/SR/s*
noise var rate	4.10E-02	*e/SR/s*

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Courtesy of Bijan Nemati

Impact to L1 PLRA Requirement (2-1)

2.2.2 Coronagraph Elements

The CGI will advance the engineering and technical readiness of key coronagraph elements needed for future missions capable of detecting and characterizing Earth-sized planets. These elements include coronagraph masks, low-order wavefront sensors, high actuator count deformable mirrors, low noise detectors, and integral field spectrographs. WFIRST would fulfill this objective by demonstrating in-space operation of the elements listed.

2.3 Project Implementation Approach

The CGI will comprise starlight suppression technologies including occulting masks, shaped pupil masks, deformable mirrors, and a low-order wavefront sensor, as well as an imaging camera and an integral field spectrograph. By conducting calibration and performance verification observations of select target stars it will demonstrate the technology to achieve high contrast at small working angles. WFIRST flight data will also be used in the validation of coronagraph performance models[a]. To be consistent with the technology demonstration designation, the coronagraph requirements are based in part on present demonstrated performance using the WFIRST coronagraph technology maturation results and in part on identified needs for a potential future exoplanet direct imaging mission.

- **Propose removing references to integral field spectrograph;**
- **Focus on requirements, not specify implementation in PLRA.**

Impact to L1 PLRA Requirement (2-2)

2.2.5 HIGH-CONTRAST DATA PROCESSING

The CGI will demonstrate advanced data processing and analysis techniques required to identify, spectrally characterize and distinguish astronomical sources in the presence of instrumental and astrophysical background noise at high contrast. WFIRST would fulfill this objective by producing photometric, astrometric, and spectrographic measurements of astrophysical object(s), including at least one point source and at least one extended object.

BTR6: (High-Contrast Imaging Spectroscopy) WFIRST shall be able to measure the spectrum of an astrophysical point source located between 0.27″ and 0.53″ from an adjacent star with a V_{AB} magnitude as dim as 5, with a flux ratio down to $5 \cdot 10^{-8}$ over an 18% bandwidth at R=50 with an SNR=10 per spectral resolution element.

Preliminary analysis shows that BTR6 is met with the prism/slit approach, therefore, this change has no impact to BTR6.

Summary

- This change (IFS → prism/slit) simplifies CGI
  - Eliminates one camera, reduces # of optics elements, reduces ~27kg mass and ~20W power
- This change maintains planet spectroscopy yield
  - Improves future star-shade performance due to SNR improvement
- Impact to PLRA:
  - Only impacts wording “integral field spectrograph”,
  - No impact to BTR6, prism/slit approach meets BTR6 requirement with margin
- Given the cost cap constraint, this change puts us in a better position at PDR
  - One less new technology to worry about
  - Consistent with community and SRB expectation to contain cost
  - It is a **HUGE** regret that we miss the opportunity to demonstrate IFS first-time in space

Backup charts

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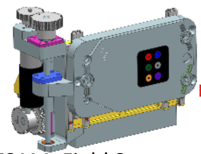
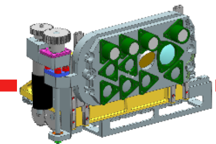
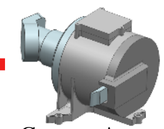
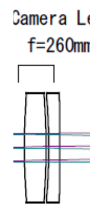
Three Key CGI Functions Preserved

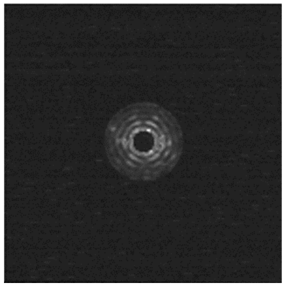

FSAM: Field Stop Alignment Mechanism


CSAM: Camera Select Alignment Mechanism


Camera Assembly (DICam)

L1 BTR5: Exoplanet imaging:
- HLC
- 10%
- 3-9 lambda/D
- Band 1
- DICAM

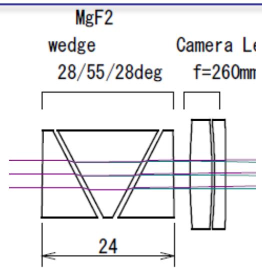


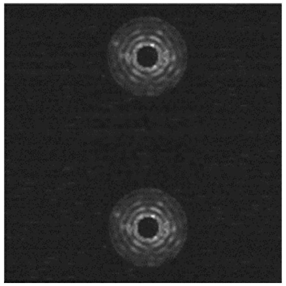


No change

- Both polarization
- All colors (within 10%)

L1: Disk imaging/polarimetry:
- SPC/HLC
- 10%
- 3-9 lambda/D, 6-19lambda/D
- Band 4
- DICAM

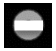


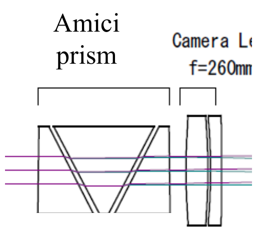


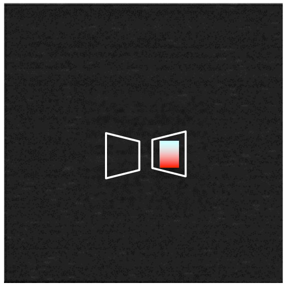
No change

- Separated images for each polarization
- All colors (within 10%)

L1: Exoplanet spectroscopy:
- SPC (or HLC)
- 15%
- 3-9 lambda/D
- Band 2 & 3
- DICAM





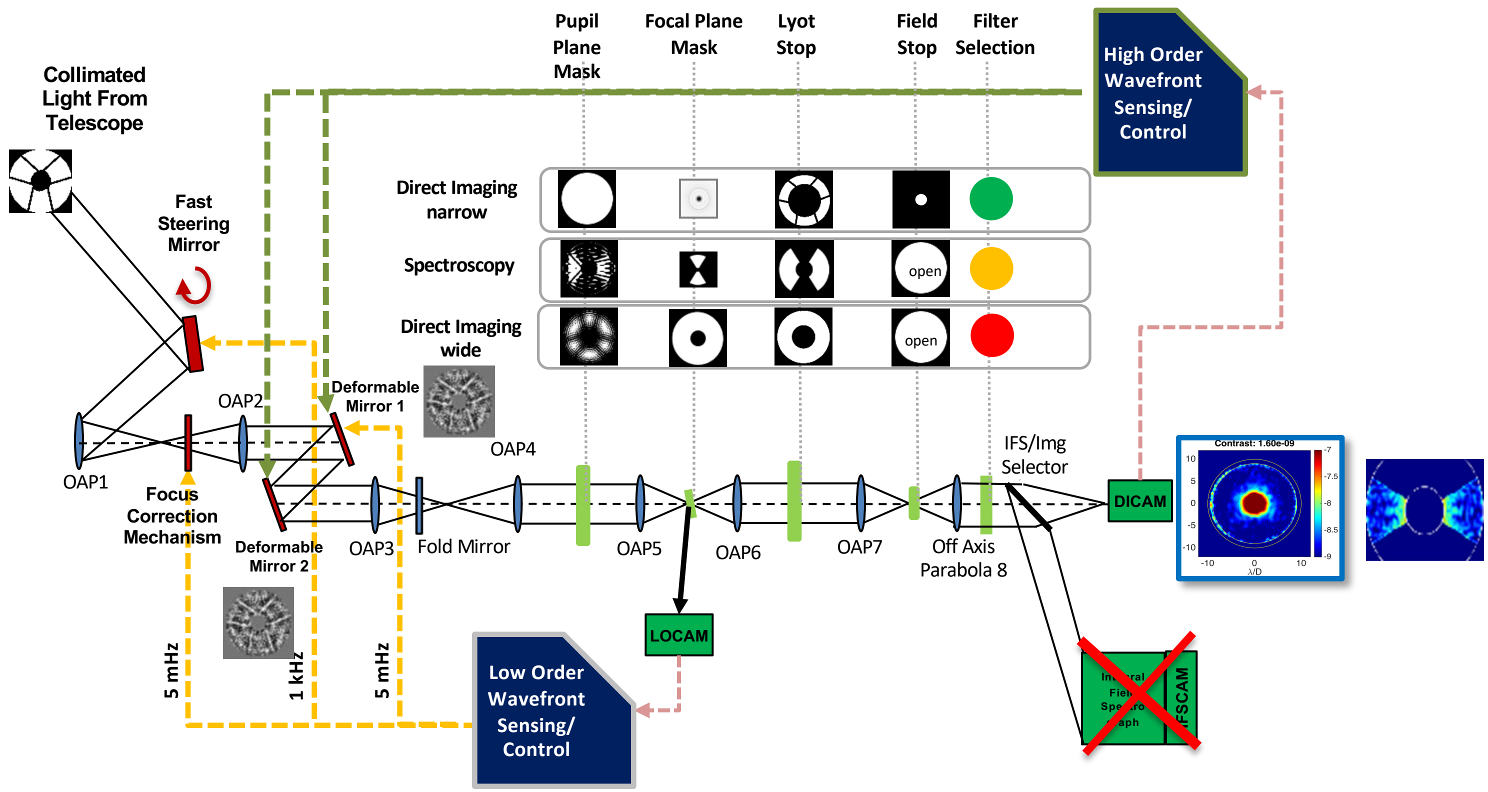


Change

- Both polarization
- Dispersed planet image (15%, R=50), with a slit size of ~1 PSF

Starshade spectroscopy mode: with dedicated SS spectrum

CGI is an Actively Controlled Optical Instrument



Proposed changes:

- **Remove the IFS optics, IFS CAM, etc**
- **Move the spectroscopy function to DI, by adding dispersion prisms on CSAM**

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Documents Affected (Title, D-Number, Rev)

WFIRST

L3 CGIRD:

CGI Optical & Imaging Performance:

673796	REQ: L3 CGI - CGI IFS Wavelength	CGI IFS data shall have absolute wavelength accuracy of <= 2 nm in filter 3 spectral band.
673795	REQ: L3 CGI - CGI Integral Field Spectrograph	CGI shall include an Integral Field Spectrograph (IFS) that operates across the wavelength range from 600-830 nm to measure spectra with a resolution of =>50 in each spatial resolution element spectrally isolated by a bandpass filter

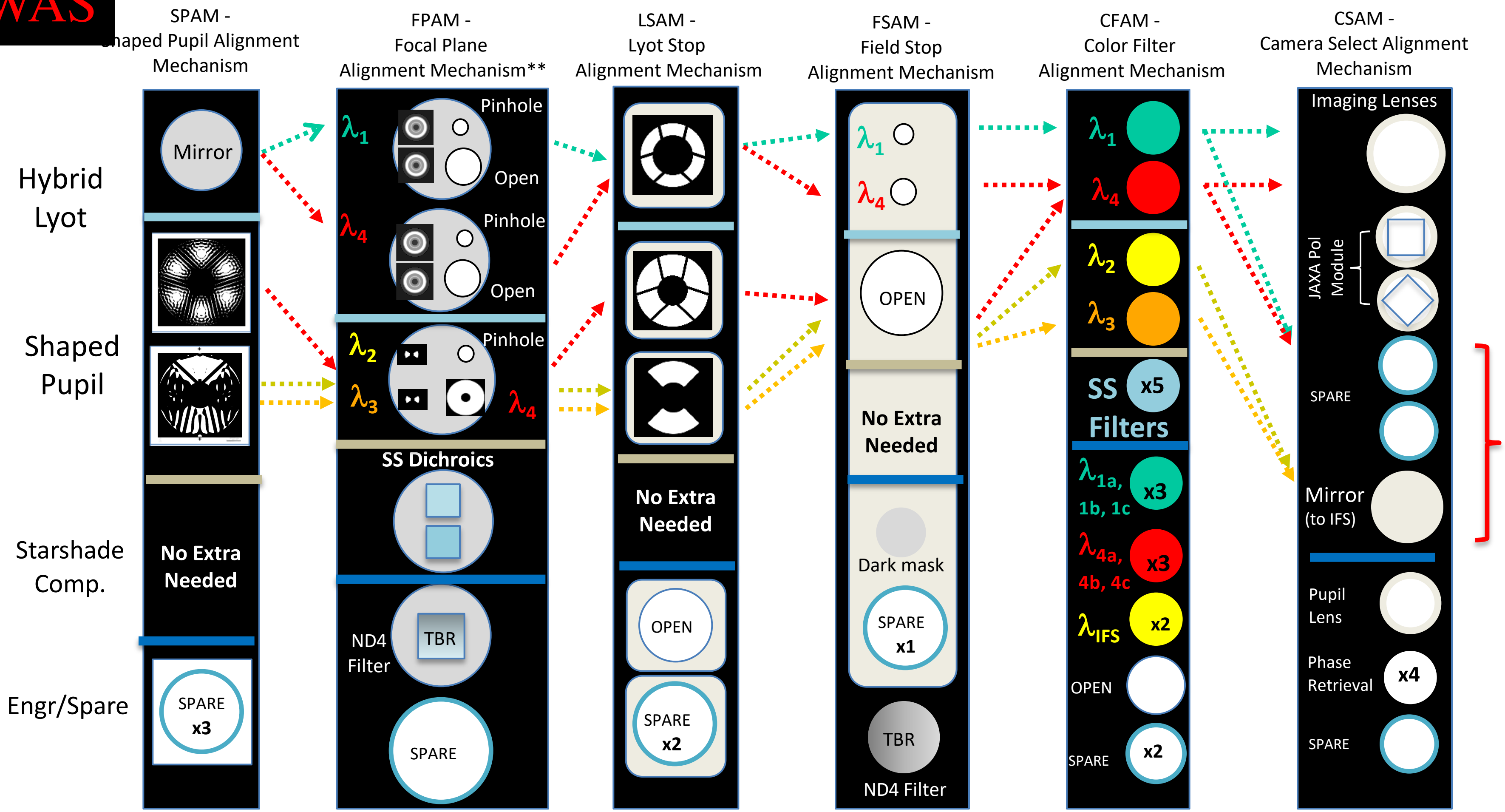
Starshade accomodation:

ID	Name	Primary Text
673723	REQ: L3 CGI - IFS Simultaneous Bandpass	The CGI IFS shall be able to simulataneously extract spectra from any 20% spectral pass band that fully overlaps with its wavelength range.
673722	REQ: L3 CGI - IFS Spectral Range	The CGI shall include an Integral Field Spectrograph (IFS) that operates in passbands of width 20% across the wavelength range from **656-1000** nm to measure spectra with a resolution of =>50 in each spatial resolution element.

CGI Mask Populations:

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

WAS

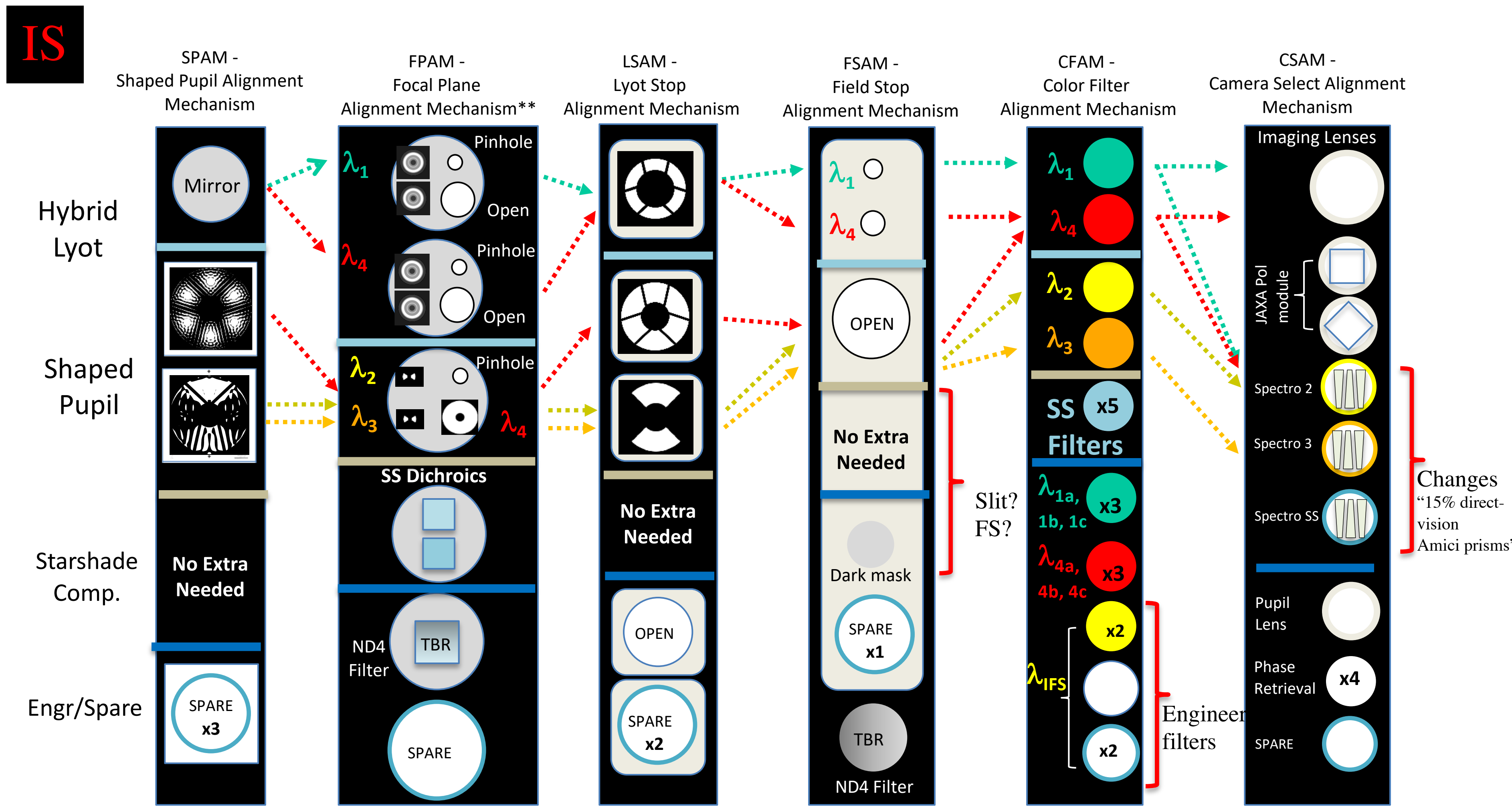


**Magnified for illustration. Each FPAM substrate can carry 7 masks or elements.

*Band submitted to CCB, not yet official

λ_1 = 575 nm, 10% | *λ_2 = 660 nm, 15%
*λ_3 = 730 nm, 15% | λ_4 = 825 nm, 10%

CGI Mask Populations:



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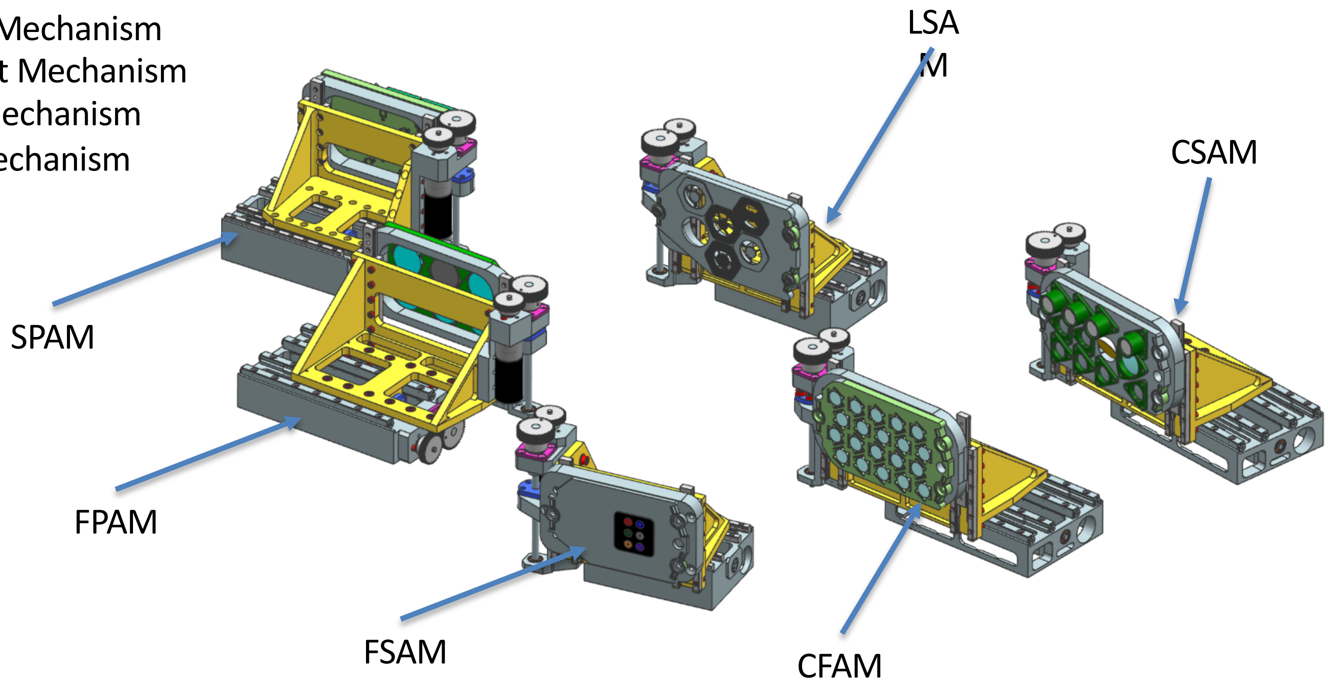
Precision Alignment Mechanism (PAM) 6X

CFAM: Color Filter Alignment Mechanism
CSAM: Camera Select Alignment Mechanism
FPAM: Focal Plane Alignment Mechanism
SPAM: Shaped Pupil Alignment Mechanism
FSAM: Field Stop Alignment Mechanism
LSAM: Lyot Stop Alignment Mechanism



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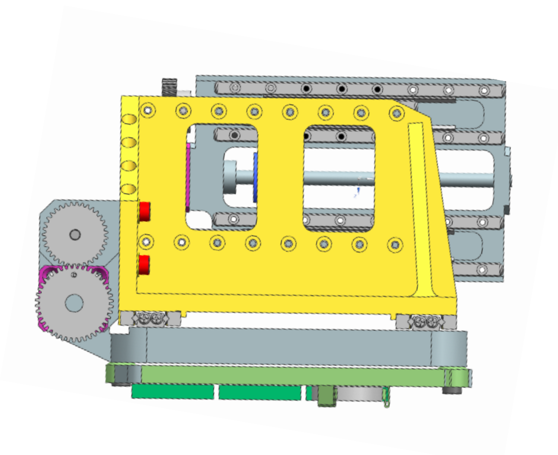
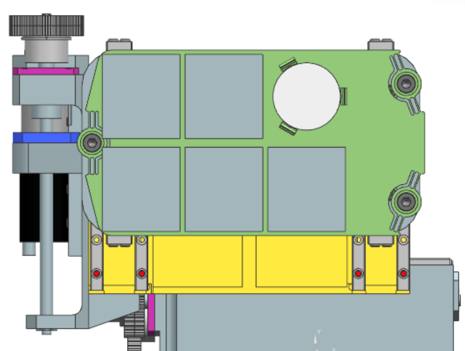
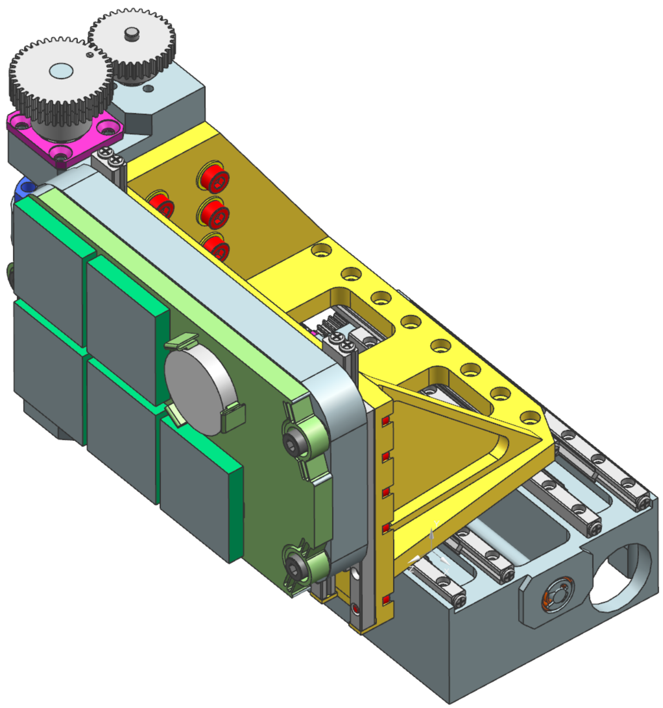
SPAM (Shaped Pupil Alignment Mechanism)







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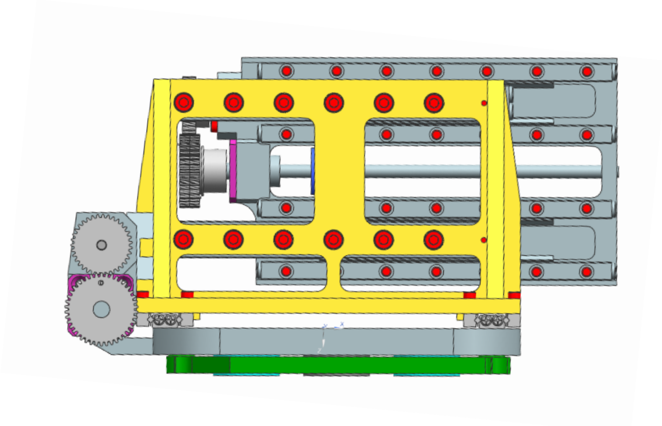
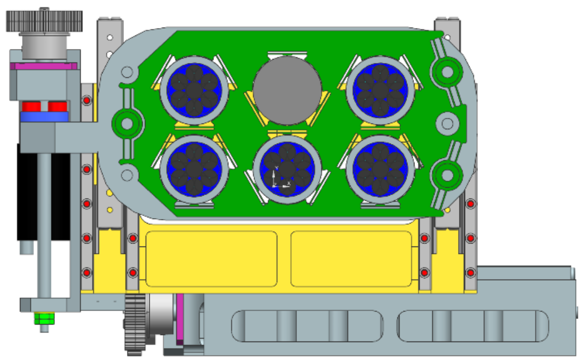
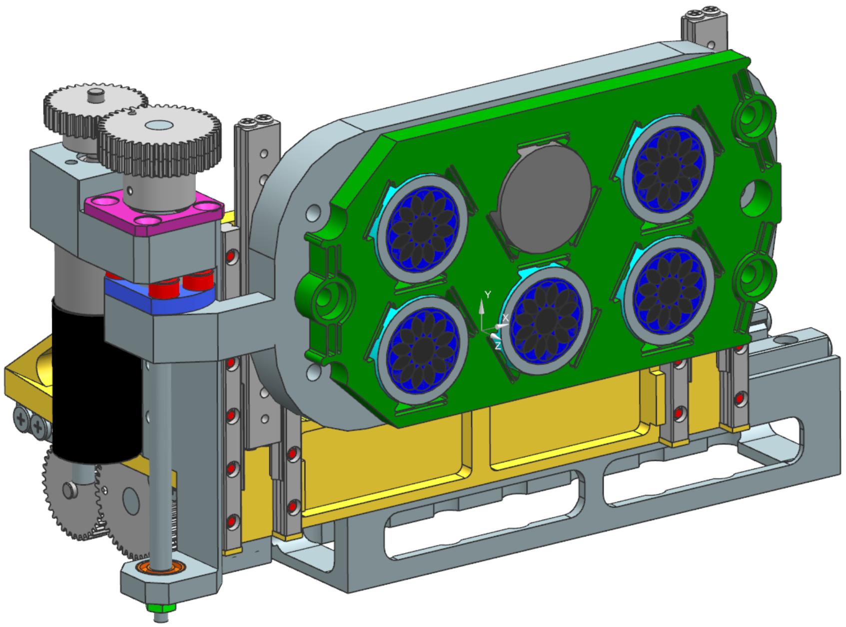
FPAM







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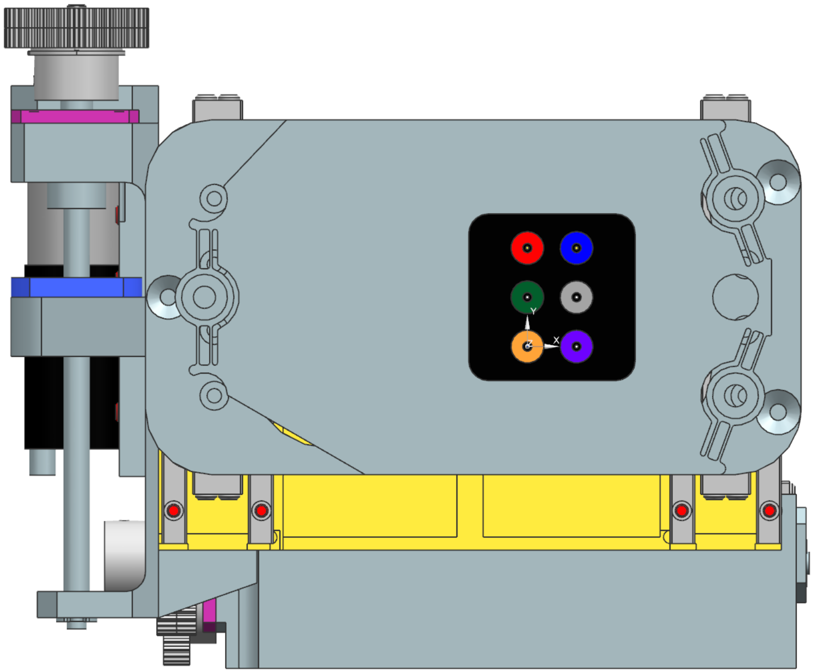
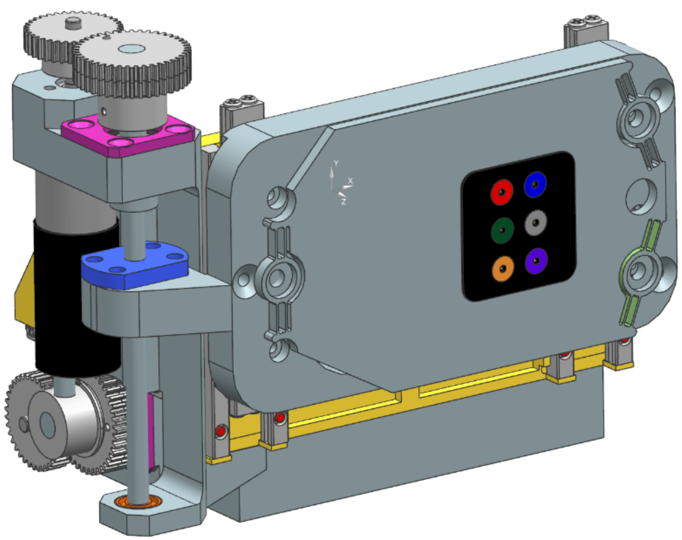
FSAM





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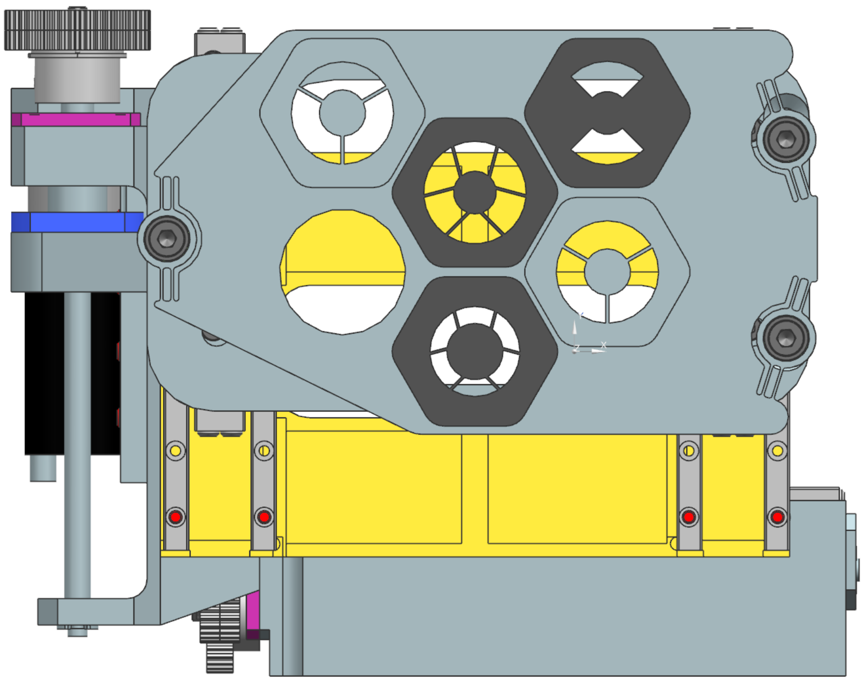
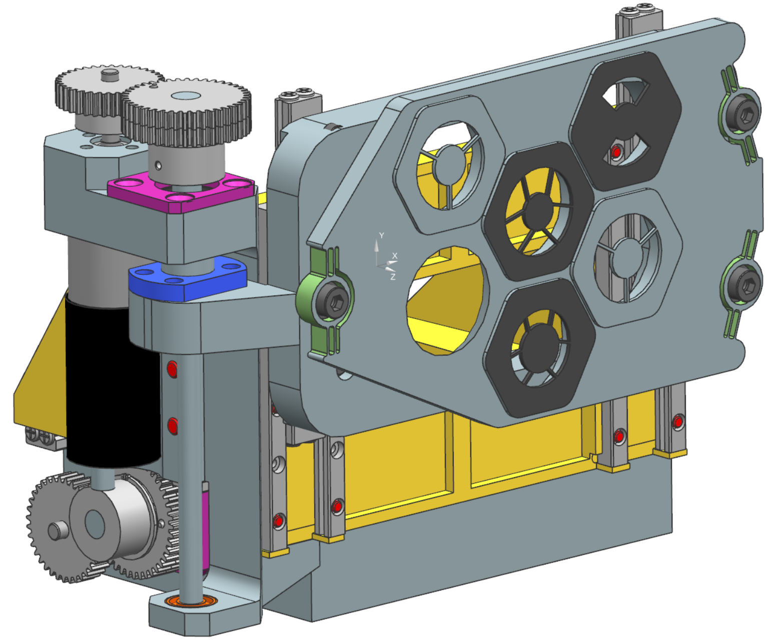
LSAM





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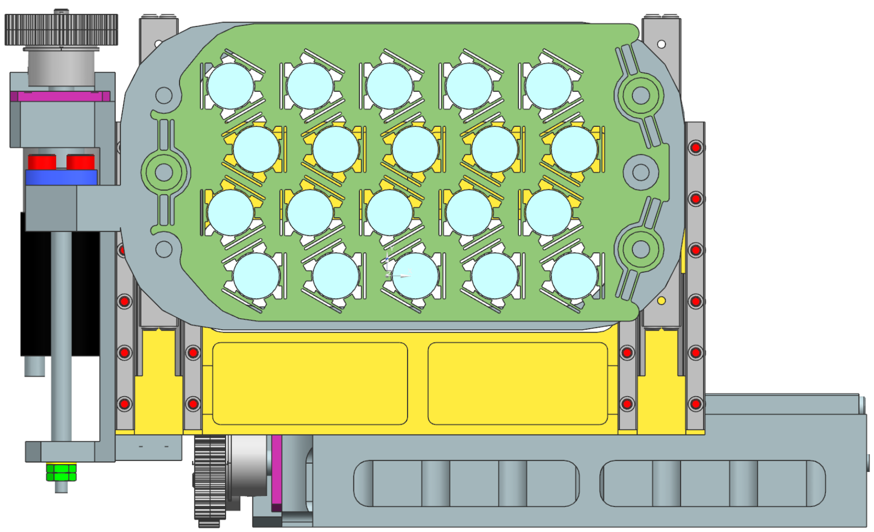
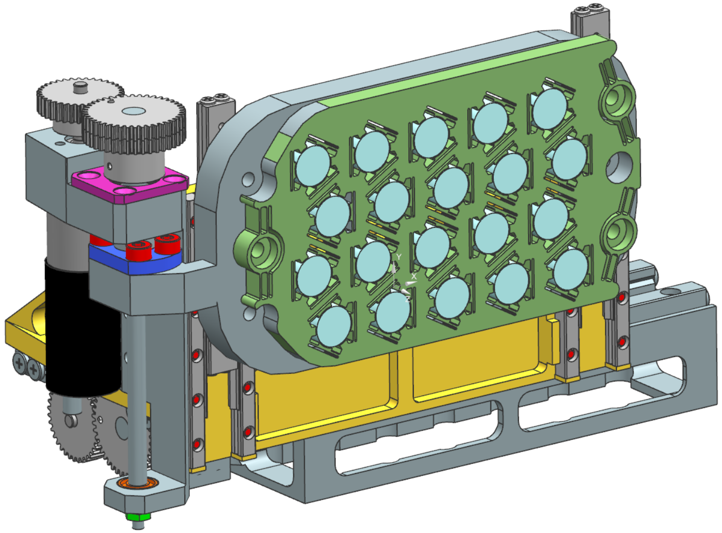
CFAM





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